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SUBJECT: TDRSS User Constraint Relaxation for ELVs, Revision 6

REFERENCES: Provided at end of document

1. SUMMARY

An effort was initiated by NASA/GSFC to determine which TDRSS user constraint requirements are most difficult and costly for manufacturers to meet and which user constraint requirements could possibly be relaxed with minimal impact on system performance. This memo addresses the issue of relaxing the user constraint requirements for the S-band Expendable Launch Vehicle (ELV) class of TDRSS users. In general, an S-band ELV user typically uses DG2 service (non-PN coded service) with BPSK or QPSK modulation, a data rate from 16 to 256 kb/sec, rate 1/2 convolutional coding and requires 1-way Doppler tracking.

Table 1 provides a summary of the existing S-band user constraint requirements as specified in the *Space Network User's Guide* [1] as well as proposed relaxed user constraint requirements for the S-band ELV class of TDRSS users. The proposed user constraint values were determined using the following approach:

1. Using analytical techniques traceable to *The Impact of TDRSS User Constraint Parameters on Bit Error Rate Performance* [2] and *The Impact of TDRSS User and Transponder Constraints on BER, Acquisition and Tracking Performance* [3], a candidate set of relaxed user constraint specifications was derived. Selection of user constraints to be relaxed was based upon comments provided by manufacturers identifying which user constraint requirements were most difficult or costly to meet. The rationale used in determining the new relaxed specification value was based upon limiting the impact to BER performance to about 0.1 dB for each user constraint relaxed.

   Appendix A of this memo provides a summary of the analytical methods used to derive the candidate set of relaxed user constraint requirements.

2. Using analytical and simulation techniques, the total impact to TDRSS BER performance due to relaxation of the user constraint requirements was determined. Based upon the simulation and analytical results, a finalized set of ELV user constraint requirements was generated. Section 2.2 of

this memo provides information on the analytical and simulation techniques used to determine the total impact to TDRSS BER performance due to the relaxation of the user constraint specifications. Appendices B, C, D and E have been provided to further validate the expected impact of relaxing the gain flatness, gain slope, phase nonlinearity, spurious outputs, frequency stability and phase noise requirements.

3. Analysis was performed to verify that the finalized ELV user constraint requirements would not adversely impact carrier tracking and carrier acquisition.

Table 1. User Constraint Relaxation for the S-Band ELV Class of TDRSS Users

Parameter		530-SNUG Specification Value[(1)]	Relaxed Specification Value	Manufacturer Comments
Spurious Outputs	In-band	≤ -30 dBc	≤ -23 dBc[(2)]	Directly drives cost of filter design, alignment and test time
	Out-of-band	≤ -15 dBc (between data bw and 2x channel bw) ≤ -30 dBc (outside of 2x channel bw)	≤ -15 dBc (between data bw and 2x channel bw) ≤ -30 dBc (outside of 2x channel bw)	
Frequency Stability (peak)	Short-Term Stability	±3 x 10^{-9} for a 1 second average time	≤ ±26 x 10^{-9} max for a 1 second average time[(3, 4, 5)]	Directly drives the cost of alignment time and test time
	Long-Term Stability	±0.1 ppm for a 5 hour observation time ±0.3 ppm for a 48 hour observation time	≤ ±3.77 ppm for a 5 hour observation time[(3, 4, 5)] ≤ ±11.3 ppm for a 48 hour observation time[(3, 4, 5)]	
	Temperature Stability	Not Specified	At any temp (±0.5° C) in the range -55° C to +85° C, the frequency variation must not exceed ±11.3 ppm	
Phase Noise[(6)]	With a Doppler tracking requirement	<u>Untracked Phase Noise</u> BPSK, data rate ≤3 kb/sec: ≤2° rms BPSK, data rate >3 kb/sec: ≤3° rms QPSK: ≤1° rms	1 Hz – 10 Hz: ≤2.0° rms 10 Hz – 100 Hz: ≤1.0° rms 100 Hz – 1 kHz: ≤1.0° rms 1 kHz – 3 MHz: ≤1.0° rms (MA) 1 kHz – 6 MHz: ≤1.0° rms (SSA)	Drives the cost of the crystal oscillator and alignment and test time
	Without a Doppler tracking requirement[(7)]	Not Applicable	1 Hz – 10 Hz: ≤50.0° rms[(8)] 10 Hz – 100 Hz: ≤6.0° rms[(8)] 100 Hz – 1 kHz: ≤2.5° rms[(8)] 1 kHz – 3 MHz: ≤2.5° rms (MA)[(8)] 1 kHz – 6 MHz: ≤2.5° rms (SSA)[(8)]	
Gain Imbalance	BPSK	±0.25 dB	±1.0 dB	Drives alignment and test time
	QPSK	±0.25 dB	±0.5 dB	
Phase Imbalance	BPSK	±3°	±9°	Drives alignment and test time
	QPSK	±3°	±5°	
Gain Flatness		≤ ±0.3 dB over ±3.5 MHz	≤ ±0.4 dB over ±0.5 MHz	Drives cost of design, alignment and test time
Gain Slope		±0.1 dB/MHz over ±3.5 MHz	Delete	
Phase Nonlinearity		≤ ±3° over ±3.5 MHz	≤ ±4° over ±0.5 MHz	Drives cost of design, alignment and test time

Untracked Spurious PM	2° rms (MA, SSA BPSK or SSA QPSK 4:1) 1° rms (SSA QPSK 1:1)	≤ 2° rms	

Table 1. User Constraint Relaxation for S-Band ELV Class of TDRSS Users (cont'd)

Parameter	530-SNUG Specification Value	Relaxed Specification Value	Manufacturer Comments
AM/PM	≤ 12°/dB	≤ 15°/dB	Drives cost of PA alignment time
AM/AM	Not specified	Not specified	
Incidental AM	≤ 5%	≤ 5%	
Symbol Asymmetry	≤ ±3%	≤ ±3%	
Symbol Rise Time	≤ 5% of symbol duration but > 35 nsec for MA and > 17 nsec for SSA	≤ 5% of symbol duration but > 35 nsec for MA and > 17 nsec for SSA	
Symbol Jitter	≤ 0.1%	≤ 0.1%	
I/Q Symbol Skew	≤ ±3%	≤ ±3%	
Bandwidth	≥ 2x maximum symbol rate	≥ 2x maximum symbol rate	

Notes:
1. All specification values traceable to the *Space Network User's Guide* except spurious outputs requirement which is traceable to the *Performance Specification for Services via the Tracking and Data Relay Satellite System*, S-805-1 [4].
2. Appendix C provides supplemental material which analytically validates the ELV spurious outputs requirement.
3. At any one temperature (±0.5° C) in the range -55° C to +85° C.
4. Transmitter oscillator required to be characterized ≤ 24 hours prior to launch and the SHO be updated. ELV user frequency uncertainty OPM required, i.e., ±40 kHz frequency sweep range required. ELV P_{rec} at TDRS must be ≥-202.0 + 12.0 dBW to ensure carrier acquisition at WSC (for ELV user frequency uncertainty OPM, C/N_0 at WSC must be ≥ 48 dB-Hz to ensure carrier acquisition). Carrier acquisition time at WSC ≤ 3 sec (P_{acq} ≥ 90%).
5. Appendix D provides supplemental material which analytically validates the ELV frequency stability requirement.
6. A 120 Hz tracking bandwidth assumed per the IR bandwidth equation in the IR Modem document [5]. MA DG2 bandwidth equation assumed the same as the SSA DG2 equation (TDRS H, I, J era will include MA DG2 capability).
7. Or can accept a Doppler tracking error greater than the specified 0.16 rad/sec, perhaps as high as 3.79 rad/sec.
8. Derivation of relaxed user phase noise requirement assumed a particular user phase noise PSD shape. User phase noise PSD shapes other than that assumed by this analysis may result in a BER impact other than that described by this memo. For this reason, the impact of user phase noise which does not meet the 530-SNUG phase noise requirement should still be analyzed on a case-by-case basis. Appendix E provides supplemental material which analytically validates the ELV phase noise requirement.

For a 256 kb/sec, rate 1/2 coded SSA DG2 BPSK user, the BER impact of relaxing the user constraint requirements from the 530-SNUG values to the values proposed in Table 1 is expected to be about 0.5 dB of additional implementation loss. This finding is based upon SPW simulation results which simulated user gain imbalance, phase imbalance, AM/AM, AM/PM, 3 dB bandwidth, gain flatness, gain slope, phase nonlinearity, data asymmetry, data transition time, incidental AM, spurious PM, and spurious outputs and analysis which examined data bit jitter, I/Q data skew, phase noise and frequency instability.

Table 2 provides a summary of the expected impact of relaxing the user constraint requirements from the 530-SNUG values to the relaxed values. Table 3 provides a summary of total implementation loss estimates for various ELV scenarios. Table 4 provides a summary of current S-band ELVs.

2. APPROACH

Using analytical techniques, a candidate set of relaxed user constraint requirements for the ELV class of TDRSS users was derived. Using SPW simulations and analytical techniques, the combined effect of the relaxed requirements on BER performance was determined. In addition to examining the impact to BER, the impact to carrier acquisition, carrier tracking, and Doppler tracking performance was also analyzed.

Table 2. Expected Impact of Relaxing User Constraint Requirements from 530-SNUG Values to ELV Values

Performance Parameter	Impact
BER	• Assuming minimum required user bandwidth, approximately 0.5 dB of additional implementation loss • Assuming nominal(1) user bandwidth, approximately 0.3 dB of additional implementation loss
Carrier Acquisition	• Assuming the ELV user frequency uncertainty OPM is required: - Transmitter frequency must be characterized ≤ 24 hours prior to launch and the SHO updated - ELV P_{rec} at TDRS must be ≥ -202.0 + 12.0 dBW to ensure carrier acquisition at WSC - Specified carrier acquisition time (P_{acq} ≥ 90%) will increase to 3 seconds(2) • Negligible impact to false-lock likelihood
Carrier Tracking	• Mean-time-to-cycle-slip expected to stay well above the 90 minute specification
Doppler Tracking Error	• Assuming 1 second averaging time, a Doppler tracking error as high as 3.79 rad/sec may result Assuming 5 second averaging time, a Doppler tracking error as high as 1.73 rad/sec may result • If 530-SNUG phase noise specification met, no impact to Doppler tracking error (i.e., ≤ 0.16 rad/sec)

Notes:
1. For BPSK, a user channel bandwidth of 8x the channel symbol rate (4.096 MHz) was used. For QPSK, a user channel bandwidth of 8x the I or Q channel symbol rate (2.048 MHz) was used.
2. This is carrier acquisition time only. Symbol synchronizer and Viterbi decoder acquisition time is in addition to this time.

Table 3. Summary of Total Implementation Loss Estimates for Various ELV Scenarios, dB

Configuration		Using 530-SNUG User Constraints	Using ELV User Constraints	Specification
Minimum User Bandwidth	BPSK	**1.25** (1.10(1) + 0.15(2))	**1.73** (1.55(1) + 0.18(2))	**2.5(3)**
	QPSK	**2.45** (1.62(1) + 0.83(2))	**2.85** (1.96(1) + 0.89(2))	
Nominal User Bandwidth(4)	BPSK(5)	**0.85** (0.70(1) + 0.15(2))	**1.11** (0.93(1) + 0.18(2))	
	QPSK	**1.69** (0.86(1) + 0.83(2))	**1.86** (0.97(1) + 0.89(2))	

Notes:

1. Contribution found via simulation. Simulated user distortions include gain imbalance, phase imbalance, AM/AM, AM/PM, 3 dB bandwidth, gain flatness, gain slope, phase nonlinearity, data asymmetry, data transition time, incidental AM, spurious PM, and spurious outputs.
2. Contribution found via analytical methods. The analytical methods used were directly applicable to uncoded service, however, they are applied here as an upper limit impact to rate 1/2 coded service. User distortions addressed analytically include data bit jitter, I/Q data skew, phase noise and frequency stability.
3. Specification traceable to *Requirements Specification for the Danzante Ground Terminal* [6].
4. For BPSK, a user channel bandwidth of 8x the channel symbol rate (4.096 MHz) was used. For QPSK, a user channel bandwidth of 8x the I or Q channel symbol rate (2.048 MHz) was used. Although it is expected that the ELV channel bandwidth will be even wider than the values assumed here, similar BER performance is expected.
5. End-to-end test data in the *Characterization Test Results Report for S-band Return Services* document [7] indicates a nominal implementation loss of 1.1 dB for an SSAR DG2 Mode 2, 256 kb/sec BPSK scenario. The test utilized the end-to-end test equipment at WSC. Information about user distortion settings was not provided and, therefore, the results cannot accurately be compared to the results presented in this table.

Table 4. Summary of S-Band ELVs

ELV	Transmit Frequency (MHz)	Data Rate (kbps)	Notes
Ariane	2203 2206 2218	240	Currently, not supported by TDRSS
Athena	2210.5 2280.5	?	Currently, not supported by TDRSS
Atlas/Centaur	2211.0	256 256, 200	SSA, DG2, BPSK, rate 1/2 SSA, DG2, QPSK with 1:1 power ratio, rate 1/2
Delta	2241.5 2252.5	640 4.8	Currently, not supported by TDRSS; Delta IV expected to use TDRSS support.
Pegasus	2288.5	?	
Titan/Centaur	2272.5	128	SSA, DG2 BPSK, Rate 1/2 coded
Titan/IUS	2217	16 64	1024 kHz subcarrier, phase modulation
SeaLaunch	2272.5 2211.0	256, 256/256 512	SSA, BPSK or QPSK SSA, BPSK

2.1 Derivation of Relaxed User Constraint Requirements

Using the analytical techniques presented in the *Impact of TDRSS User Constraint Parameters on Bit Error Rate* document [2] and *The Impact of TDRSS User and Transponder Constraints on BER, Acquisition and Tracking Performance* [3], a candidate set of relaxed user constraint specifications was derived. Appendix A provides documentation of the derivation of the candidate set of ELV user constraint requirements.

The rationale for selecting a user constraint requirement to be relaxed was based upon comments provided by manufacturers identifying which user constraint requirements were most difficult or costly to meet. The rationale used in determining the new relaxed specification value was based upon limiting the impact to the rate 1/2 coded BER performance to about 0.1 dB for each user constraint relaxed.

2.2 Combined Effect Analysis

Analytic and simulation techniques were used to determine the combined impact of relaxing the user constraint requirements. As many user distortion parameters as possible were simulated in SPW simulations using the Code 450 TDRSS end-to-end link simulation models, however, some user distortions could not be simulated in SPW. Analytic techniques including the use of the Phase Noise Analysis Tool (PNAT) software were used to determine the impact of user distortions not simulated in SPW. The BER degradations found using SPW and using analytic methods were added together to generate the total impact to the BER due to the relaxation of the 530-SNUG user constraint requirements.

2.2.1 SPW Simulation Approach

Using the Code 450 end-to-end link simulation models, Bit-Error-Rate (BER) simulations were performed with the distortion parameters set as indicated in Tables 5, 6, and 7. The resultant BER curves generated by the simulations were compared at 10^{-5} BER. The difference between the two performance curves at 10^{-5} was identified as the impact of relaxing the user constraint requirements from the 530-SNUG values to the ELV values for the particular user distortions simulated in SPW.

2.2.2 Analytic Techniques Approach

For the user constraints which were not simulated, analytic techniques were used to determine the impact of relaxing the specification. Using the techniques presented in References [2] and [3], the individual impact of each specification relaxation was evaluated. These individual BER degradation amounts were added together to form the BER degradation at 10^{-5} for the particular user distortions examined analytically. It should be noted that the analytical techniques used to compute the individual degradation values are only applicable to uncoded service. It is expected, however, that these values can be used as an upper bound on the impact to rate 1/2 coded service.

Table 5 indicates which user distortions were simulated and which were analyzed analytically. It should be noted that only two of the user distortions which were examined analytically were relaxed. These relaxed specifications include frequency stability and phase noise. The PNAT software was used for the phase noise analysis.

2.2.3 Combined Effect Calculation

The combined effect of relaxing the user constraint requirements from the 530-SNUG values to the ELV values was calculated by adding the degradation found via simulation to the degradation found through analysis. This approach should be accurate because, in general, the majority of the user constraint specifications which were relaxed were simulated. Any combined effects of relaxing the specifications would appear in the simulations. On the other hand, the analytic approach is not expected to account for combined effects, however, very few of the user constraints which were relaxed were addressed analytically.

2.3 Additional Performance Analysis

In addition to examining the impact to the BER, the impact to carrier acquisition, carrier tracking and Doppler tracking was also examined. The impact to carrier acquisition and carrier tracking was determined using analytical phase-locked loop techniques. The impact to Doppler tracking was determined using the analytical PNAT software.

2.3.1 Carrier Acquisition

To determine the impact of user constraint requirement relaxation on carrier acquisition, the user constraints which can most impair carrier acquisition were identified. These user constraints include frequency stability and spurious outputs. The impairments which were considered were the likelihood of false-lock and the likelihood of failure to achieve carrier lock.

Table 5. USAT Simulation Test Conditions(1)

Parameter	Baseline Simulations (530-SNUG User Constraints)	Relaxed User Constraint Simulations
Service	SSA DG2 Mode 2	SSA DG2 Mode 2
Modulation	BPSK, QPSK	BPSK, QPSK
Data Rate, kb/sec	256.0 (BPSK) 256.0 (QPSK)	256.0 (BPSK) 256.0 (QPSK)
Data Format	NRZ-L	NRZ-L
Code Rate	1/2	1/2
SSL C/N_0, dB-Hz	67.06	67.06
I/Q Power Ratio	1.0:1.0	1.0:1.0
I/Q Phase Rotation, deg.	0.0	0.0
Gain Imbalance, dB	0.25	1.0 (BPSK) 0.5 (QPSK)
Phase Imbalance, deg.	3.0	9.0 (BPSK) 5.0 (QPSK)
AM/AM, dB/dB	1.0	1.0
AM/PM, deg./dB	12.0	15.0
3 dB Bandwidth, MHz	1,024 kHz (BPSK) 512 kHz (QPSK) and 4,096 kHz (BPSK) 2,048 kHz (QPSK)	1,024 kHz (BPSK) 512 kHz (QPSK) and 4,096 kHz (BPSK) 2,048 kHz (QPSK)
Roll-off, dB/MHz	25.0 (BPSK) 50.0 (QPSK)	25.0 (BPSK) 50.0 (QPSK)
Gain Flatness, dB	±0.3	±0.4
Gain Slope, dB/MHz	0.1	0.8
Phase Nonlinearity, deg.	±3.0	±4.0
Incidental AM, %	5.0 @ 240 Hz(2)	5.0 @ 240 Hz(2)
Spurious PM, deg. Rms	2.0° rms @ 1 kHz(2) (BPSK) 1.0° rms @ 1 kHz(2) (QPSK)	2.0° rms @ 1 kHz(2) (BPSK) 1.0° rms @ 1 kHz(2) (QPSK)
Spurious Outputs, dBc	-30 dBc @ 1.5 kHz(2) -15 dBc @ 768 kHz(2)	-23 dBc @ 1.5 kHz(2) -15 dBc @ 768 kHz(2)
Data Asymmetry, %	3.0	3.0
Data Transition Time, % of symbol duration	> 5	> 5
Data Bit Jitter, %	Not simulated, examined analytically	Not simulated, examined analytically
Frequency Stability, ppm	Not simulated, examined analytically	Not simulated, examined analytically

Phase Noise, deg. rms	Not simulated, analyzed in PNAT	Not simulated, analyzed in PNAT
Notes: 1. Shading indicates distortion parameters which were relaxed for the ELV class of TDRSS users. 3. Frequencies arbitrarily selected.		

Table 6. TDRS Simulation Test Conditions

Parameter	Value
AM/AM, dB/dB	0.5
AM/PM, deg./dB	5.5
3 dB Bandwidth, MHz	4.096[(1)]
Roll-off, dB/MHz	8.44
Gain Flatness, dB	±0.5
Gain Slope, dB/MHz	0.1
Phase Nonlinearity, deg.	±5.0

Notes:
1. To minimize the simulation sampling frequency and, therefore, simulation run-time, the TDRS channel bandwidth was reduced. This TDRS channel bandwidth is still large compared to the USAT channel bandwidth and, therefore, will have a negligible impact on BER.

Table 7. STGT Simulation Test Conditions

Parameter	Value
3 dB Bandwidth, MHz	4.096[(1)]
Roll-off, dB/MHz	6.193
Gain Flatness, dB	±0.3
Gain Slope, dB/MHz	0.1
Phase Nonlinearity, deg.	±3.0

Notes:
1. To minimize the simulation sampling frequency and, therefore, simulation run-time, the STGT channel bandwidth was reduced. This STGT channel bandwidth is still large compared to the USAT channel bandwidth and, therefore, will have a negligible impact on BER.

The user distortion most likely to drive false-lock likelihood is spurious outputs. The ELV spurious outputs requirement was derived based upon limiting the BER impact to about 0.1 dB. To ensure that this relaxed specification did not appreciably increase the likelihood of false-lock, analysis was performed to assess the spur level relative to the carrier power throughout the entire carrier acquisition process. The algorithm used by the IR to select the carrier frequency amidst various possible spurs was examined and the likelihood of false-lock assessed. Appendix C provides additional information on this analysis approach.

The user distortion most likely to delay carrier acquisition is oscillator frequency instability. The ELV frequency stability specification was derived based primarily upon the carrier acquisition capabilities (frequency sweeping capabilities and carrier tracking loop capabilities) of the Integrated Receiver (IR). This approach should ensure that delays or failure to achieve carrier acquisition due to frequency instability are very unlikely. Appendix D of this memo provides a description of the approach used to determine the relaxed frequency stability requirement and the considerations given to the carrier acquisition process.

2.3.2 Carrier Tracking

To determine the impact of user constraint requirement relaxation on carrier tracking, the user constraints which can most impair carrier tracking were identified. These user constraints include frequency stability, phase noise, spurious PM and spurious outputs. Of these user constraints, frequency stability, phase noise and spurious outputs were relaxed. These relaxed values were derived considering the effects to carrier tracking, such as, mean-time-to-cycle-slip and loss of carrier lock. Appendices C, D and E provide additional information on the approach used to determine the impact of spurious outputs, frequency instability and phase noise on carrier tracking.

2.3.3 Doppler Tracking

The user constraint which most impacts Doppler tracking error was identified to be phase noise. PNAT was used to determine the effect relaxing the phase noise requirement has on Doppler tracking error.

It should be noted that if a particular ELV mission requires Doppler tracking and cannot tolerate a Doppler tracking error greater than the 0.16 rad/sec specification, the relaxed phase noise requirement cannot be used.

3. RESULTS

3.1 Simulation Results

TDRSS end-to-end link BER simulations were performed with simulation parameters set as listed in Tables 5, 6, and 7. Figure 1 provides the results for BPSK modulation, and Figure 2 provides the results for QPSK modulation.

For BPSK, the impact of relaxing the user constraint requirements from the 530-SNUG specified values to the ELV values is about 0.45 dB. For QPSK, the impact of relaxing the user constraint requirements from the 530-SNUG specified values to the ELV values is about 0.34 dB. It should be recalled that these degradation amounts only represent a portion of the impact of relaxing the user constraint specification values as all user distortions were not simulated. Table 5 identifies which user distortions were simulated, and Table 1 identifies which user constraint requirements were relaxed.

In addition to performing simulations using the 530-SNUG minimum specified user channel bandwidth, simulations were performed using nominal ELV channel bandwidths. Figures 3 and 4 present these simulation results for BPSK and QPSK, respectively. As expected, the simulation curves presented in Figures 3 and 4 are closer to the theoretical curve than the results presented in Figures 1 and 2.

Figure 1. BPSK Simulation Results Using 530-SNUG Minimum Required Channel Bandwidth

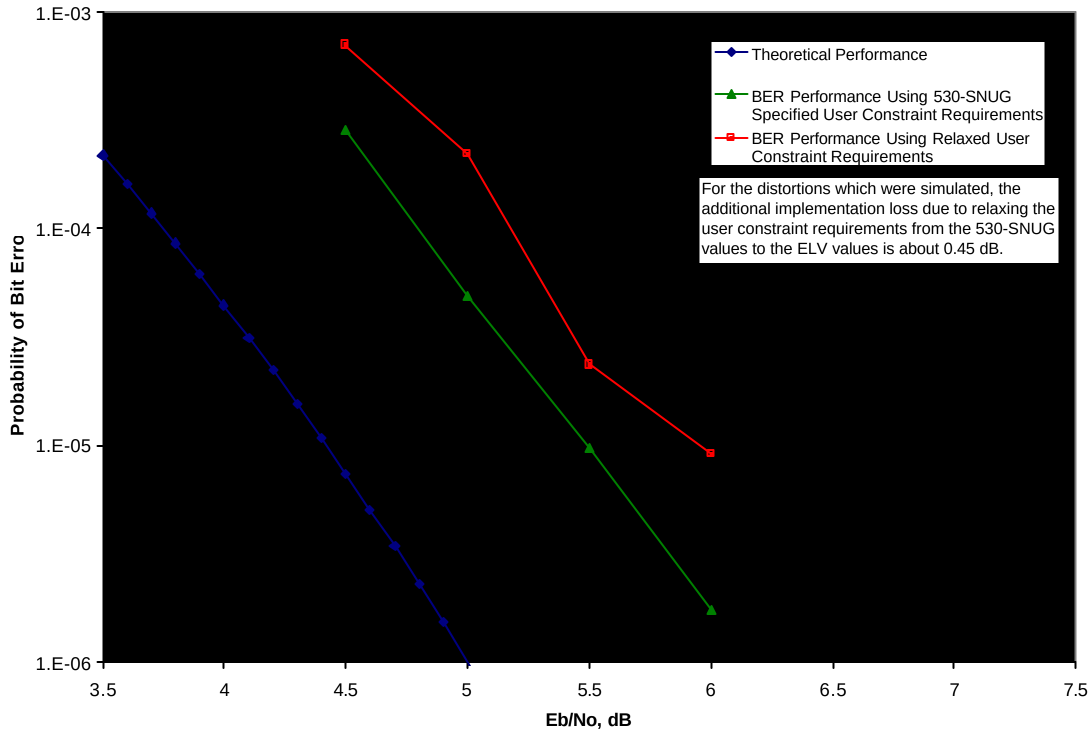


Figure 2. QPSK Simulation Results Using 530-SNUG Minimum Required Channel Bandwidth

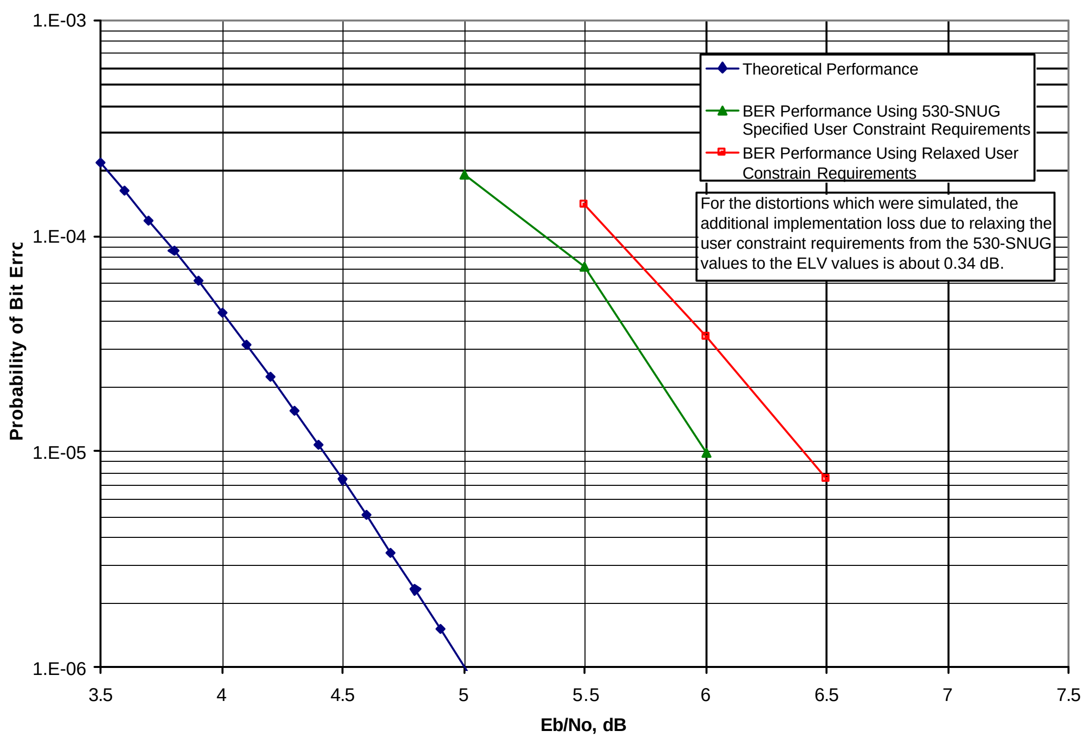


Figure 3. BPSK Simulation Results Using Nominal ELV Channel Bandwidth

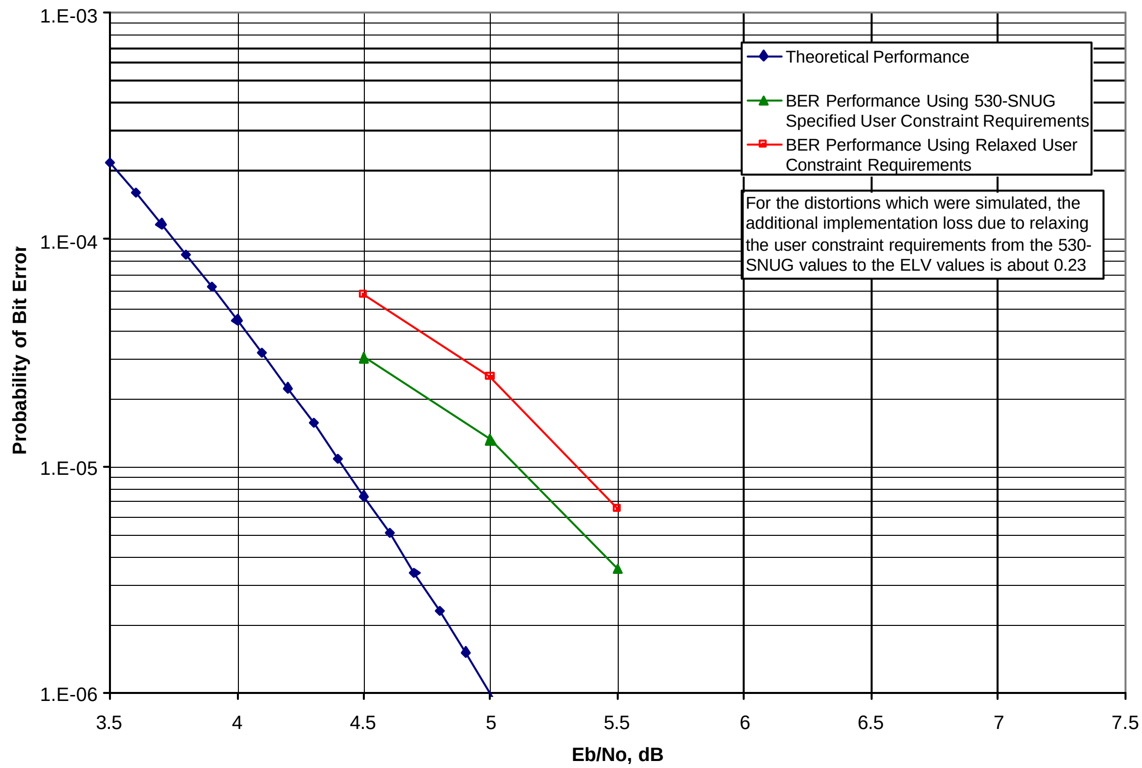
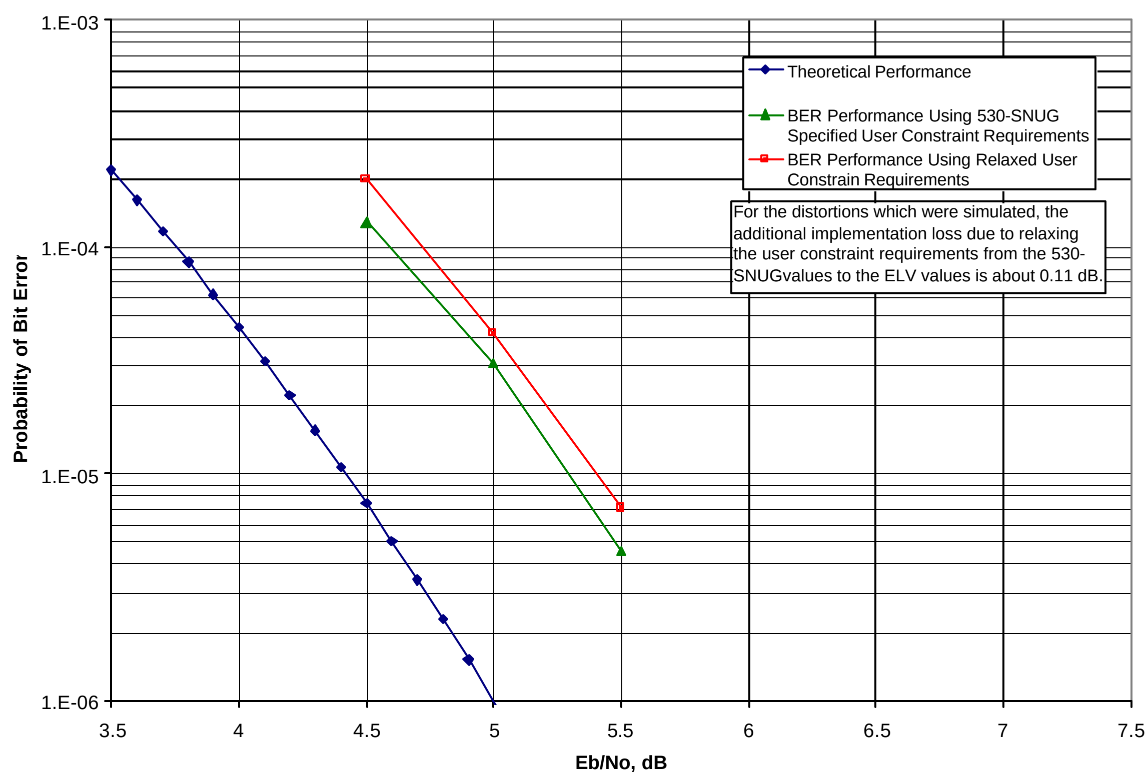


Figure 4. QPSK Simulation Results Using Nominal ELV Channel Bandwidth



3.2 Analytical Results

The only user distortion requirements which were relaxed but not simulated were frequency stability and phase noise. The relaxing of the frequency stability requirement will have a negligible impact on the BER. The BER impact of relaxing the phase noise requirement was determined using PNAT and is provided in Table 8.

Also addressed analytically using PNAT was the impact of user constraint relaxation on the Doppler tracking error. For ELV missions which require Doppler tracking and a Doppler tracking error of less than the specified 0.16 rad/sec [5], the existing 530-SNUG phase noise requirement was not relaxed and, therefore, there will be no impact. For missions which do not have a Doppler tracking requirement or can tolerate a Doppler tracking error greater than the specified 0.16 rad/sec amount, the phase noise requirement was relaxed and a Doppler tracking error as high as 3.79 rad/sec (1 sec averaging time) can be expected.

Table 8. Summary of BER Degradation for the 530-SNUG, S-805-1 and ELV Phase Noise Scenarios[1, 2]

Parameter		530-SNUG	S-805-1	Relaxed
User contribution to total untracked phase error[3]		≤3° rms (BPSK) ≤1° rms (QPSK)	1.64° rms	4.36° rms
System contribution to total untracked phase error[4]		3.92° rms	3.92° rms	3.92° rms
Total untracked phase error		4.92° rms (BPSK) 4.03° rms (QPSK)	4.24° rms	5.86° rms
BER degradation due to untracked phase error[5]	BPSK	≈ 0.10 dB	≈ 0.07 dB	≈ 0.13 dB
	QPSK	≈ 0.19 dB	≈ 0.15 dB	≈ 0.25 dB

Notes:
1. Phase noise results computed using PNAT. Consult References [8] and [9] for additional details on the PNAT model.
2. The service scenario assumed is that of SSA DG2 Mode 2, 256 kb/sec, rate 1/2 coding and no Doppler tracking requirement. The results for MA service should be similar to the results shown here.
3. User contribution only.
4. All other contributors besides the user, i.e., relay system and thermal noise.
5. BER impact to rate 1/2 coded service.

3.3 Combined Results

Based upon the simulation results presented in Section 3.1 and the analytical results presented in Section 3.2, the total increase in the implementation loss due to relaxing the user constraint requirements from the 530-SNUG values to the ELV values is expected to be approximately 0.5 dB (assumes ELV channel bandwidth equal to 530-SNUG minimum required bandwidth and BPSK modulation). Table 9 provides a summary of this calculation.

4. CONCLUSION

Using the 530-SNUG minimum required user channel bandwidth, the impact of relaxing the user constraint requirements from the 530-SNUG values to the ELV values is expected to increase the implementation loss by less than 0.5 dB, increase the carrier acquisition time to a maximum of three seconds, increase the Doppler tracking error to perhaps as high as 3.79 rad/sec (assuming a Doppler tracking error higher than the specified 0.16 rad/sec can be tolerated) and have a negligible impact on carrier tracking. Additional impacts include the requirement that the ELV transmitter be characterized 24 hours before launch, and the ELV P_{rec} at TDRS be $\geq$-202.0 + 12.0 dBW to ensure carrier acquisition at WSC.

Table 9. Additional Implementation Loss Due to Relaxing the User Constraint Requirements from 530-SNUG Values to the ELV Values(1)

Component	BPSK	QPSK
Contribution from distortions which were simulated(2)	≈ 0.45 dB	≈ 0.34 dB
Contribution from distortions which were analyzed analytically(3)	≈ 0.03 dB	0.06 dB
Total	≈ 0.48 dB	≈ 0.40 dB

Notes:
1. Assumes an ELV channel bandwidth equal to the 530-SNUG minimum required bandwidth.
2. User distortions which were simulated and whose required values were relaxed include gain imbalance, phase imbalance, gain flatness, gain slope, phase nonlinearity, AM/PM and spurious outputs.
3. User distortions which were addressed analytically and whose required values were relaxed include frequency stability and phase noise.

5. REFERENCES

[1] *Space Network User's Guide*, Revision 7, 530-SNUG, NASA/GSFC, November 1995.

[2] *The Impact of TDRSS User Constraint Parameters on Bit Error Rate Performance*, STI/E-TR-7017, Richard S. Orr and Leonard Schuchman/STel, 7 October 1977.

[3] *The Impact of TDRSS User and Transponder Constraints on BER, Acquisition and Tracking Performance*, STI/E-TR-8013, Aaron Weinberg, Stanford Telecom, 21 March 1978.

[4] *Performance Specification for Services via the Tracking and Data Relay Satellite System*, Revision C, S-805-1, NASA/GSFC, July 1989.

[5] *IR Modem Control Processor Implementation Design Document*, 530-WSC-0044, 5 April 1996.

[6] *Requirements Specification for the Danzante Ground Terminal*, 530-SRD-Danzante, NASA/GSFC, 15 August 1994.

[7] *Characterization Test Results Report for S-Band Return Services*, 534-RPT-PL6-S_BAND, Systems Engineering and Analysis Support Network Technology Group, NASA/GSFC, September 1995.

[8] *TDRSS and TDRS II Phase Noise Analysis Final Report*, TR93077, Matt Griffin, John Wesdock, et al., Stanford Telecomm, 30 September 1993.

[9] *TDRS H, I, J Phase Noise Modeling and End-to-End Phase Noise Calculations Based on CDR Information*, SES-531-60059, Matt Griffin, John Wesdock, Stanford Telecomm, 17 October 1997.

[10] *SSA Equipment HWCI Specification*, STGT-HE-04-05, GE Aerospace, NASA/GSFC, September 1990.

[11] *Performance and Design Requirements for the Second Generation TDRSS User Transponder*, STDN No. 203.8, NASA/GSFC, November 1984.

[12] *Introduction to Communications Engineering*, Second Edition, Robert M. Gagliardi, John Wiley & Sons, ©1978.

[13] *Coherent Spread Spectrum Systems*, Jack Holmes, John Wiley & Sons, ©1982.

APPENDIX A:
Derivation of a Candidate Set of ELV User Constraint Requirements

This section derives a candidate set of ELV user constraint requirements. The analysis provided here only addresses the impact of each parameter individually. The combined impact of relaxing the user constraint requirements is examined in the main body of the memo. The rationale for selecting a user constraint to be relaxed is based upon comments provided by manufacturers identifying which user constraint requirements are most difficult or costly to meet. The rationale used in determining the new relaxed specification value is based upon limiting the BER impact to rate 1/2 coded service to about 0.1 dB for each user constraint relaxed.

This appendix is only intended to demonstrate the initial analytical rationale for selecting an ELV requirement. Simulations were used to finalize these ELV requirements.

A.1 Overview

This appendix provides information on the derivation of ELV gain imbalance, phase imbalance, gain flatness, phase nonlinearity, AM/PM as well as an examination of the impact of data bit jitter on BER. It was determined that the derivation and validation of some ELV user constraints should be documented in a manner much more detailed than that presented in this appendix, therefore, user constraints gain slope, spurious outputs, frequency stability and phase noise have been given their own appendix sections. Appendices B, C, D and E provide the comprehensive derivation documentation for the ELV gain slope, spurious outputs, frequency stability and phase noise requirements.

Before examining the methods of this appendix and Appendices B, C, D and E, it should be noted that the analytical methods used here are generally applicable to uncoded service only. It is expected that the impact to rate 1/2 coded service (as is used for ELV service) will be less than that shown in this appendix.

A.2 ELV Candidate User Constraint Derivation

A.2.1 Gain Imbalance

Modulator gain imbalance is the worst-case ratio of the power in one signal phase state to the power in another signal phase state. For BPSK, gain imbalance is the ratio of the power in the +1 phase state to the power in the -1 phase state. For QPSK, gain imbalance is the worst-case ratio of the power in the I or Q channel +1 phase state to the power in the I or Q channel -1 phase state.

Reference [2] derives the impact of gain imbalance on uncoded BPSK and QPSK BER as follows:

$$\Delta\frac{E_b}{N_0} \geq 10\log\left(\frac{2(1+h)}{(1+\sqrt{h})^2}\right) \quad \text{for BPSK where } h = P_+/P_-$$

$$\Delta \frac{E_b}{N_0} \leq 10\log\left[\left(\cos q_e - \sqrt{h} \cdot \sin q_e\right)^{-2}\right] \quad \text{for QPSK}$$

where

h = gain imbalance

$$q_e = \frac{1}{4}\left[q_4(\sqrt{h} \cdot r) - q_4(r)\right] \quad \text{where} \quad q_4(r) = \tan^{-1}\left(\frac{4(r^{-1} - r)}{r^{-2} - 6 + r^2}\right) \text{ and } r^2 = \text{ desired Q/I channel power ratio}$$

The bound derived for the BPSK case is a lower bound and generally becomes inaccurate for gain imbalances greater than about 0.5 dB. Reference [2] does also derive an exact impact of gain imbalance on uncoded BPSK, however, the equation cannot be expressed in terms of a delta Eb/No. An exact impact of gain imbalance on uncoded BPSK modulation written in the form of a probability of bit error equation is as follows:

$$P(e\,|\,h) = \frac{1}{2}\text{erfc}\left[\sqrt{\frac{E_b}{N_0}\left(\frac{2h}{1+h}\right)}\right] + \frac{1}{2}\text{erfc}\left[\sqrt{\frac{E_b}{N_0}\left(\frac{2}{1+h}\right)}\right] \quad \text{for BPSK}$$

This equation is plotted in Figure A-1 for a gain imbalance of 0.25 dB and a gain imbalance of 1.0 dB. Also included in the figure is the impact of gain imbalance on QPSK probability of bit error. Using Figure A-1, the uncoded BER impact of relaxing the gain imbalance requirement from 0.25 dB to 1.0 dB for BPSK and from 0.25 dB to 0.5 dB for QPSK can be summarized as shown in Table A-1. Table A-1 also discusses the impact to carrier acquisition and carrier tracking.

Figure A-1. Impact of Gain Imbalance on <u>Uncoded</u> BPSK and QPSK Performance

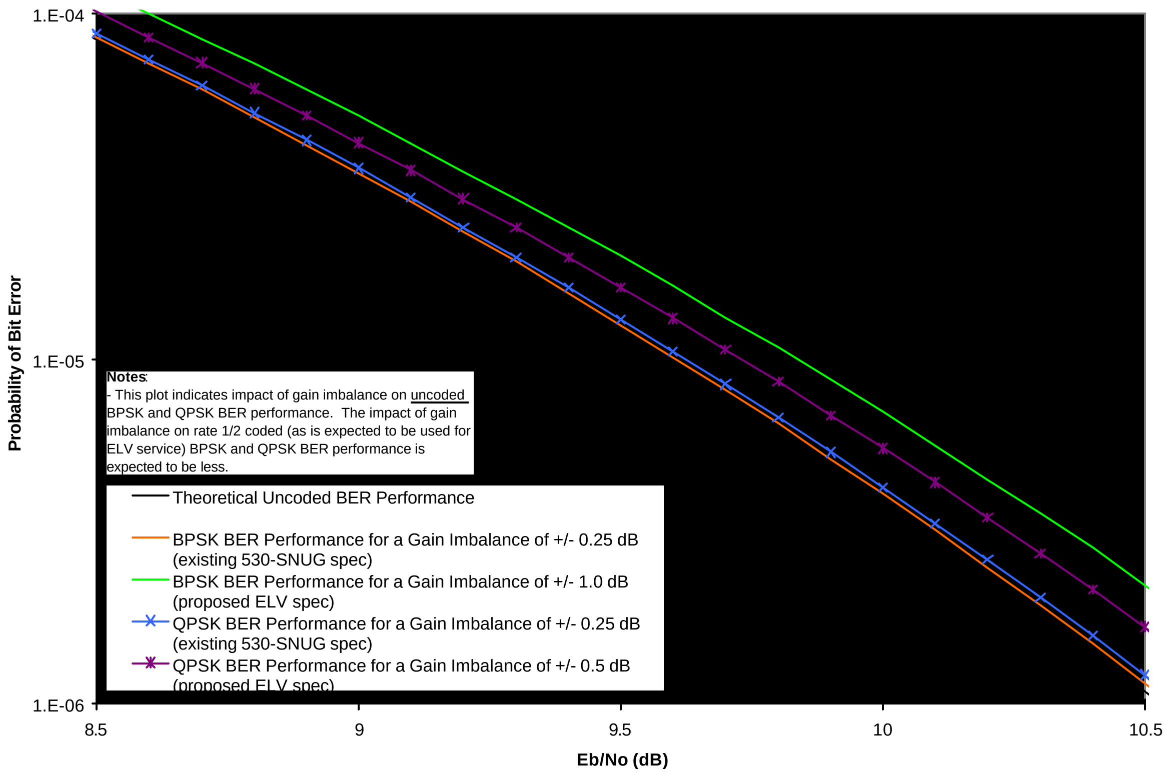


Table A-1. Impact of Relaxing Gain Imbalance Specification

Performance Criteria	Expected Impact			
	BPSK		QPSK	
	Using 530-SNUG Spec	Using Relaxed Spec	Using 530-SNUG Spec	Using Relaxed Spec
BER degradation [1]	≈ 0.02 dB	≈ 0.26 dB	≈ 0.04 dB	≈ 0.14 dB
Carrier Acquisition	Negligible impact	Negligible impact	Negligible impact	Negligible impact
Carrier Tracking	Negligible impact	Negligible impact	Negligible impact	Negligible impact
Notes: 1. BER impact to uncoded service. Impact to rate 1/2 coded service will be less.				

A.2.2 Phase Imbalance

BPSK modulator phase imbalance is defined as the steady-state difference between the phase states of BPSK modulated 1's and 0's relative to 180°. QPSK modulator phase imbalance is defined as $f = \max(\Psi_i - \Psi_{ideal})$, where Ψ_i are the four actual phase angles and Ψ_{ideal} is the value of each phase angle under distortion-free conditions.

Reference [2] derives the impact of phase imbalance on uncoded BPSK modulation BER performance. This impact can be written as follows:

$$\Delta \frac{E_b}{N_o} = 10\log\left[\sec^2\left(\frac{q}{2}\right)\right] \quad \text{where } q = \text{phase imbalance}$$

The impact of phase imbalance on QPSK is slightly more involved. Reference [3] does examine the impact of phase imbalance on QPSK and provides a probability of bit error equation for calculating the impact. This equation has been plotted in Figure A-2 for a phase imbalance of 3° and 5°. Also provided in the figure is the impact of 3° and 9° of phase imbalance on BPSK probability of bit error. Using Figure A-2, the uncoded BER impact of relaxing the phase imbalance requirement from 3° to 9° for BPSK and from 3° to 5° for QPSK can be summarized as shown in Table A-2. Table A-2 also discusses the impact to carrier acquisition and carrier tracking.

Figure A-2. Impact of Phase Imbalance on Uncoded BPSK and QPSK Performance

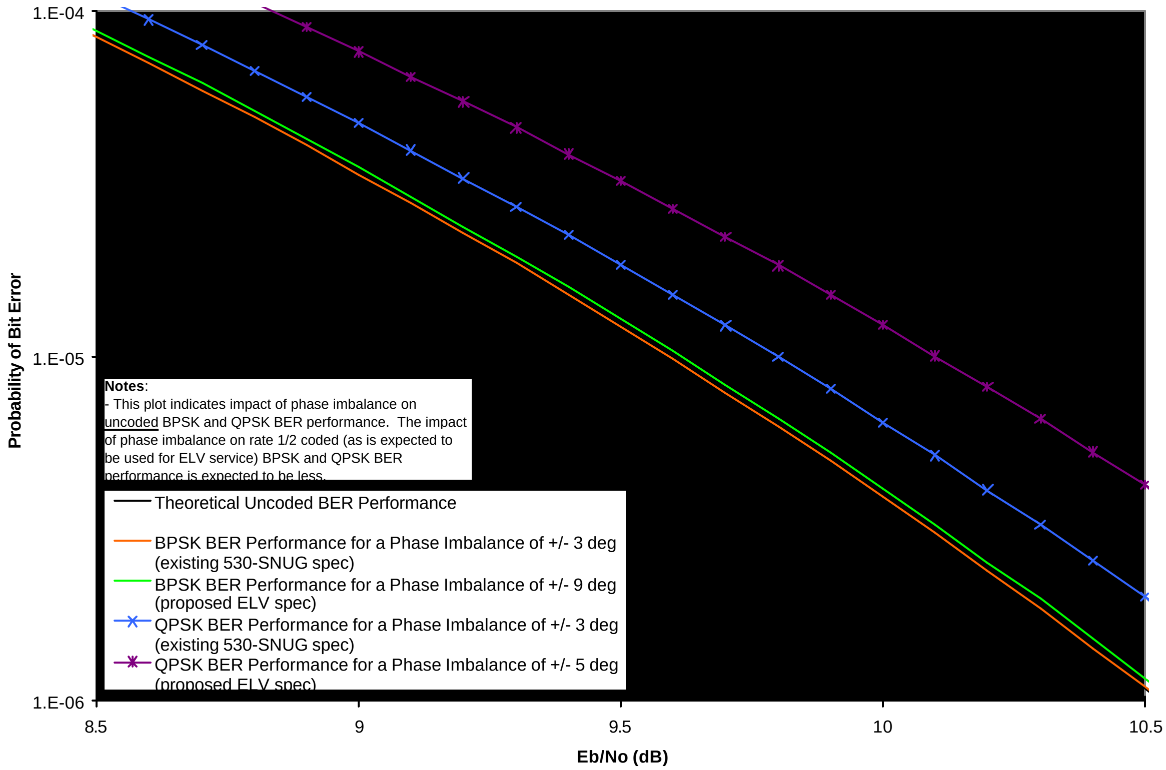


Table A-2. Impact of Relaxing Phase Imbalance Specification

Performance Criteria	Expected Impact			
	BPSK		QPSK	
	Using 530-SNUG Spec	Using Relaxed Spec	Using 530-SNUG Spec	Using Relaxed Spec
BER degradation [1]	≈ 0.003 dB	≈ 0.03 dB	≈ 0.20 dB	≈ 0.50 dB
Carrier Acquisition	Negligible impact	Negligible impact	Negligible impact	Negligible impact
Carrier Tracking	Negligible impact	Negligible impact	Negligible impact	Negligible impact

Notes:
1. BER impact to uncoded service. Impact to rate 1/2 coded service will be less.

A.2.3 Gain Flatness

Gain flatness is the peak deviation of the gain from the best horizontal fit to the actual gain-vs-frequency relationship over the bandwidth of interest. Reference [2] puts forth analysis which can be used to show an upper bound on the impact of gain flatness on uncoded BER performance is as follows:

$$\Delta\frac{E_b}{N_0} \leq GF_p \quad \text{where } GF_p = \text{peak gain flatness in dB}$$

See Appendix B of this document for additional information on the impact of gain flatness on BER. Table A-3 summarizes the impact of relaxing the peak-to-peak gain flatness specification from 0.6 dB to 0.8 dB.

Table A-3. Expected Impact of Relaxing Gain Flatness Requirement

Performance Criteria	Expected Impact	
	Using 530-SNUG Spec	Using Relaxed Spec
BER Degradation(1)	≈ 0.3 dB	≈ 0.4 dB
Carrier Acquisition	Negligible impact	Negligible impact
Carrier Tracking	Negligible impact	Negligible impact
Notes: 1. BER impact to uncoded service. Impact to rate 1/2 coded service will be less		

A.2.4 Phase Nonlinearity

Phase nonlinearity is the peak deviation of phase from the best linear fit reference phase vs. frequency relationship over the bandwidth of interest. Phase nonlinearity impacts the BER in a manner similar to gain flatness. Reference [2] derives an upper bound on the impact of phase nonlinearity on uncoded BER performance to be as follows:

$$\frac{E_b}{N_0} \leq 10\log\left[(1-b)^2\right] \quad \text{where } b = \text{peak phase nonlinearity in radians}$$

See Appendix B of this document for additional information on the impact of phase nonlinearity on BER. Table A-4 summarizes the impact of relaxing the phase nonlinearity specification from ±3° to ±4°.

Table A-4. Expected Impact of Relaxing Phase Nonlinearity Requirement

Performance Criteria	Expected Impact	
	Using 530-SNUG Spec	**Using Relaxed Spec**
BER Degradation(1)	≈ 0.47 dB	≈ 0.63 dB
Carrier Acquisition	Negligible	Negligible
Carrier Tracking	Negligible	Negligible
Notes: 1. BER impact to uncoded service. Impact to rate 1/2 coded service will be less.		

A.2.5 AM/PM

AM/PM is the worst case ratio of the slope of an RF output phase to an RF input power over a range of operation of a high power amplifier. Reference [2] derives the impact of AM/PM on uncoded BER performance to be as follows:

$$\frac{E_b}{N_0} = 20\log(\cos q_p)\ \mathrm{dB}$$

where

$$q_p = K_p \cdot 20\log(1 + m)$$

$$K_p = \text{AM/PM value}$$

$$m \approx 0.1 \text{ for AM/PM values around 12 deg/dB}$$

Table A-5 summarizes the impact of relaxing the phase nonlinearity specification from 12° to 15°.

Table A-5. Expected Impact of Relaxing AM/PM Requirement

Performance Criteria	Expected Impact	
	Using 530-SNUG Spec	**Using Relaxed Spec**
BER Degradation(1)	≈ 0.19 dB	≈ 0.30 dB
Carrier Acquisition	AM/PM can raise the level of spurs in the transmitted PSD. Examination of spur levels using SPW indicates minimal likelihood of false-lock	Examination of spur levels using SPW indicates negligible increase in spur levels over 530-SNUG scenario. Negligible increase in the likelihood of false-lock
Carrier Tracking	Negligible impact	Negligible impact
Notes: 1. BER impact to uncoded service. Impact to rate 1/2 coded service will be less.		

A.2.6 Symbol Jitter

Although the symbol jitter requirement is not relaxed for ELVs, it is important to document the expected absolute BER degradation due to symbol jitter. A definition of symbol jitter should first be identified then the BER degradation due to symbol jitter be derived. Symbol jitter is the input signal peak clock frequency jitter as a percent of the symbol (data) clock rate. Additionally, symbol jitter rate is the input signal peak clock jitter rate as a percent of the symbol clock. The impact of symbol jitter and symbol jitter rate can be computed using the following steps:

- Compute the clock frequency jitter PSD as follows (assuming random jitter):

$$S_f(f) = \frac{(\Delta f \cdot R_s)^2}{9 \cdot f_{\max} \cdot R_s} \qquad \mathrm{Hz}^2/\mathrm{Hz} \qquad \mathrm{f} \le \mathrm{f}_{\max}$$

$$S_f(f) = 0 \qquad \mathrm{f} > \mathrm{f}_{\max}$$

  where

  Δf = peak frequency deviation = symbol jitter = $3s$

  R_s = symbol rate

  $f_{\max}$ = maximum jitter rate

- Compute the clock phase jitter PSD from the clock frequency jitter as follows:

$$S_p(f) = \frac{S_f(f)}{(2 \cdot p \cdot f)^2} \qquad \mathrm{rad}^2/\mathrm{Hz}$$

- Compute the variance of the phase jitter not tracked by the symbol synchronizer as follows:

$$s_p^2 = \int_0^{f_{\max}} S_p(f) \cdot \left|H_{ss}(f)\right|^2 df$$

  where

  $H_{ss}(f)$ = Symbol synchronizer transfer function

- Using the curves presented in Reference [8], determine the BER degradation from s_p.

Assuming a symbol rate, R_s, of 256 kb/sec, a symbol jitter of 0.1%, a symbol jitter rate of 0.1% and a symbol synchronizer loop bandwidth of $2 \cdot f_{\max} \cdot R_s$ Hz, the standard deviation of the untracked phase jitter was found to be 2.84° rms. Assuming this untracked phase jitter impacts the BER in a manner reasonably similar to that of untracked phase error, the BER impact (relative to no symbol jitter) is about 0.05 dB for rate 1/2 coded BPSK and 0.10 dB for rate 1/2 coded QPSK.

APPENDIX B:
Analytical Validation of the Gain Flatness, Gain Slope and Phase Nonlinearity Requirement

This appendix primarily examines how the 530-SNUG gain slope requirement can be relaxed for the ELV class of TDRSS users. Gain slope, however, cannot be examined without also considering gain flatness. Also considered in this appendix is the impact of phase nonlinearity which is very similar to that of gain flatness.

B.1 Background

It can be shown that a sinewave in the frequency domain, produces two impulses in the time domain as shown below:

<u>Frequency Domain</u>		<u>Time Domain</u>
$a \cdot \cos(2\pi f T_0)$	$\Leftrightarrow$	$\frac{a}{2}\delta(t - T_0) + \frac{a}{2}\delta(t + T_0)$

Furthermore, it can be shown, using the Fourier series, that any magnitude response can be represented as the summation of many sinewaves. To understand how magnitude response passband variations impact BER, the impact of a simple sinewave passband shape must be examined.

A sinewave passband can be written as follows in the frequency domain:

$$H(f) = 1 + a \cdot \cos(2\pi f T_0)$$

where

$a =$ amplitude of the sinewave

$f =$ frequency (or frequency relative to carrier if at RF)

$\frac{1}{T_0} =$ period of sinewave (in Hz)

Using the Fourier transform pair given previously, it can be shown that the output of such a channel when an input of s(t) is applied is as follows (disregarding all other effects of the channel such as bandlimiting, phase nonlinearity, etc):

$$y(t) = s(t - T) + \frac{a}{2}s(t - T - T_0) + \frac{a}{2}s(t - T + T_0)$$

where T is some arbitrary filter delay and is greater than T_0.

It can be seen that a passband with a sinewave ripple will produce a leading echo and a lagging echo of the desired signal. These echoes cause Inter-Symbol Interference (ISI). A maximum ISI impact will occur when T_0 is greater than one symbol length. Since the peak gain slope will drive T_0, gain slope can have an significant impact on the ISI scenario. It should also be noted, however, that peak gain flatness also has a significant impact on the ISI scenario. The peak gain flatness will drive the amplitude of the echoes, meanwhile, the peak gain slope will drive the delay of the echoes.

Since maximum degradation will occur when τ_0 is greater than one symbol duration, a threshold can be computed for the gain slope above which maximum degradation will occur. This threshold gain slope can be computed roughly as follows:

$GS_{thres} \approx 4T_s \cdot GF_{peak}$ dB/MHz where T_s is the symbol duration

Gain slopes above this threshold amount will, in general, result in worst-case degradation. If when deriving the ELV gain flatness specification the worst-case gain slope is assumed, it is possible to delete the gain slope requirement for ELVs. Section B.2 addresses the derivation of the ELV gain flatness requirement. For the derivation, a worst-case gain slope amount is assumed, therefore, it is possible to delete the ELV gain slope requirement.

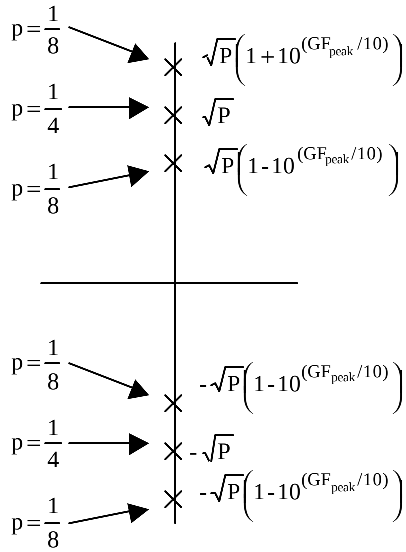
It should be noted that magnitude responses of more complicated shape than a sinewave can be considered, however, all scenarios reduce down to some combination of sinewaves of varying amplitudes and periods.

B.2 Impact of Gain Flatness on Uncoded BER Performance

Reference [2] puts forth an analysis based upon the eye diagram closure due to ISI. This approach makes several worst-case assumptions and, therefore, is likely to produce a conservative estimate.

Figure B-1 provides a scatterplot of samples taken at the middle of the symbol in the presence of gain flatness. It can be seen that the various scenarios of ISI introduce scattering into the plot (the various scenarios of ISI are a transition to a +1 with a +1 interfering, a transition to a -1 with a +1 interfering, no transition, etc.). If the worst-case ISI scenario is assumed, it can be seen that the Eb/No will be degraded by approximately GF_{peak} dB.

Figure B-1. Scatterplot of Middle of the Symbol Samples with Gain Flatness



B.3 Impact of Phase Nonlinearity on Uncoded BER Performance

It can be shown that a sinusoid phase nonlinearity distortion produces a similar degradation situation as gain flatness. Sinusoidal phase nonlinearity generates an infinite series of echoes in the time domain. Considering just the largest echo pair, the following equation has been derived by Reference [2] to determine the BER degradation due to phase nonlinearity:

$\frac{E_b}{N_0} \leq 10\log\left[(1-b)^2\right]$ where b = peak phase nonlinearity in radians

APPENDIX C:
Analytical Validation of the ELV Spurious Outputs Requirement

This appendix examines how the 530-SNUG spurious outputs requirement can be relaxed for the ELV class of TDRSS users. The BER impact of this specification relaxation will be less than 0.14 dB. The impact to carrier acquisition and tracking is expected to be negligible.

C.1 Background

Spurious outputs are defined as the relative transmission power contained in all unwanted spurs that exist in a specified segment of the RF carrier's frequency spectrum. Spurious outputs on the transmitter signal can be represented mathematically as follows:

$$s(t) = \cos\left[w_c t + q + f_d(t)\right] + \sum_{i=1}^{M} p_i \cdot \cos(w_{p_i} t + q_{p_i})$$

where

q = arbitrary phase of carrier

$f_d(t)$ = data stream

$\sum_{i=1}^{M} p_i \cdot \cos(w_{p_i} t + q_{p_i})$ = spurious outputs

q_{p_i} = arbitrary phase of individual spurious outputs

When a signal containing spurious outputs is received at the ground terminal and mixed with the phase-locked carrier, the low-pass component of the output is as follows: (assuming PLL steady-state operation):

$$s(t) \cdot 2\cos(w_c t + q)\big|_{LP} = \cos f_d(t) + \sum_{i=1}^{M} p_i \cdot \cos\left((w_{p_i} - w_c)t + (q_{p_i} - q)\right)$$

The output of the data detector can be written as follows (assuming ideal $f_d(t)$):

$$\frac{1}{T}\int_0^T s(t) \cdot 2\cos(w_c t + q)\big|_{LP} \cdot dt = 1 + \sum_{i=1}^{M} p_i \left[\frac{\sin\left(\frac{(w_{p_i} - w_c)T}{2}\right)}{\frac{(w_{p_i} - w_c)T}{2}}\right] \cdot \cos(q_{p_i} - q)$$

where

T = Integration time of data detector

The summation represents the interference due to the spurious components. The effect of the spurious terms on BER can be written as follows:

$$P(e \,|\, p, \Delta q_p) = P_e\left[\sqrt{\frac{E_b}{N_0}} \cdot \left(1 + \sum_{i=1}^{M} p_i S_i \cdot \cos \Delta q_{p_i}\right)\right]$$

where

p = collection of spurious output amplitudes

$\Delta q_p =$ collection of spurious output demodulated phases

$$S_i = \left[\frac{\sin\left(\frac{(w_{p_i} - w_c)T}{2}\right)}{\frac{(w_{p_i} - w_c)T}{2}} \right]$$

As the Δq_{p_i} terms are expected to be uniformly distributed, they can be averaged out. The probability of bit error can now be written simply as a function of the spurious output amplitudes and frequencies. The following bound has been derived for the probability of bit error as a function of spurious output amplitudes and frequencies:

$$P(e|p) \leq P_e \left[\sqrt{\frac{\frac{E_b}{N_0}}{1 + \frac{p}{2} r \cdot \sum_{i=1}^{M} (p_i S_i)^2}} \right]$$

Substituting for S_i, the Eb/No degradation can be written as follows:

$$\Delta \frac{E_b}{N_0} \leq 1 + \frac{p}{2} \cdot \frac{E_b}{N_0} \cdot \sum_{i=1}^{M} \left(p_i \cdot \frac{\sin\left(\frac{(w_{p_i} - w_c)T}{2}\right)}{\frac{(w_{p_i} - w_c)T}{2}} \right)^2$$

For further information on analytically determining the impact of spurious outputs on BER, *The Impact of TDRSS User Constraint Parameters on Bit Error Rate Performance* document [2] should be consulted.

C.2 ELV Spurious Outputs Specification Derivation

Using the formula derived in Section C.1, the BER impact of relaxing the spurious outputs specification from the 530-SNUG specified value of 30 dBc to the proposed ELV value of 23 dBc has been computed for uncoded service. Table C-1 summarizes this expected impact. The Eb/No assumed for the calculations was 7.2 dB (4.2 dB + 3 dB), the spur frequency was assumed to be the carrier frequency which is worst-case.

Table C-1. Expected Impact of Relaxing Spurious Outputs Requirement

Performance Criteria	Expected Impact	
	Using 530-SNUG Spec	Using Relaxed Spec
BER Degradation	≈ 0.04 dB	≈ 0.18 dB
Carrier Acquisition	Negligible likelihood of false-lock	Negligible likelihood of false-lock
Carrier Tracking	Negligible impact	Negligible impact

C.3 Carrier Acquisition and Tracking Impact

This section examines the impact of relaxing the spurious outputs requirement from -30 dBc to -23 dBc on IR carrier acquisition and carrier tracking. Worst-case analysis is presented examining the increase in false-lock likelihood and loss-of-lock likelihood.

Before examining the impact to false-lock likelihood, a short overview of the IR carrier acquisition process must be provided. This overview begins following the downconversion of the receive signal to the 370 MHz intermediate frequency. Figure C-1 is provided for reference. The carrier acquisition process can be summarized as follows:

1. The IF signal is downconverted by a frequency pre-corrected 300 MHz mixing signal to approximately 70 MHz. Due to frequency uncertainties in the receive signal caused by ephemeris error and user transmitter frequency instability, the downconverted signal is not exactly at 70 MHz.
2. The received signal is further downconverted to approximately baseband by a locally-generated, noncoherent 70 MHz signal. The 70 MHz mixing signal is generated in two quadrature phases, and both are used in the downconversion process to produce the baseband quadrature components of the receive signal.
3. These quadrature signals are next each integrated over by an Integrate-and-Dump (I/D) identified as the "IR initial I/D" in Reference [5]. The initial I/Ds operate at a rate of $2.1 \cdot R_s$ MHz where R_s is the individual channel symbol rate. This rate of $2.1 \cdot R_s$ tends to pass the majority of the receive signal power while limiting the noise.
4. Following integration, the signal is complex squared (if BPSK modulation or 4:1 UQPSK modulation) or complex quaded (if 1:1 QPSK modulation) to remove the data. It should be noted that this process will cause the frequency offset to increase by a factor of two (if squared) or four (if quaded). It should be further noted, however, that no DC component will result due to the use of a complex square or quad.
5. Following removal of data, the quadrature components are each integrated again by an I/D identified as the "IR demod I/D" in Reference [5]. The demod I/Ds operate at a rate of 170 kHz for the standard ELV user frequency uncertainty OPM implementation.
6. Using the samples output by the IR demod I/D, a 1024-point FFT is performed. It should be noted that the frequency range covered by using each value output by the IR demod I/D in the FFT is $\pm$85 kHz (170/2 kHz). Since the squaring operation caused the frequency offset to be as high as 80 kHz, the IR demod I/D rate was set to cover this range.
7. A peak search is performed on the FFT samples. When the maximum value has been identified, it is compared to a noise threshold. If the value is greater than the threshold, the corresponding frequency of the sample point is identified as 2x the carrier frequency offset, and the tracking loop NCO is adjusted appropriately.

To examine the increase in false-lock likelihood due to relaxing the spurious outputs requirement, a worst-case analysis is performed. It is assumed that the frequency predicted by the IR happens to exactly correspond to the location of a -23 dBc spur and the actual carrier is 40 kHz from the IR-predicted frequency. Figure C-2, Frame A provides a graphical representation of this scenario.

Figure C-1. Overview of the IR Signal Processing

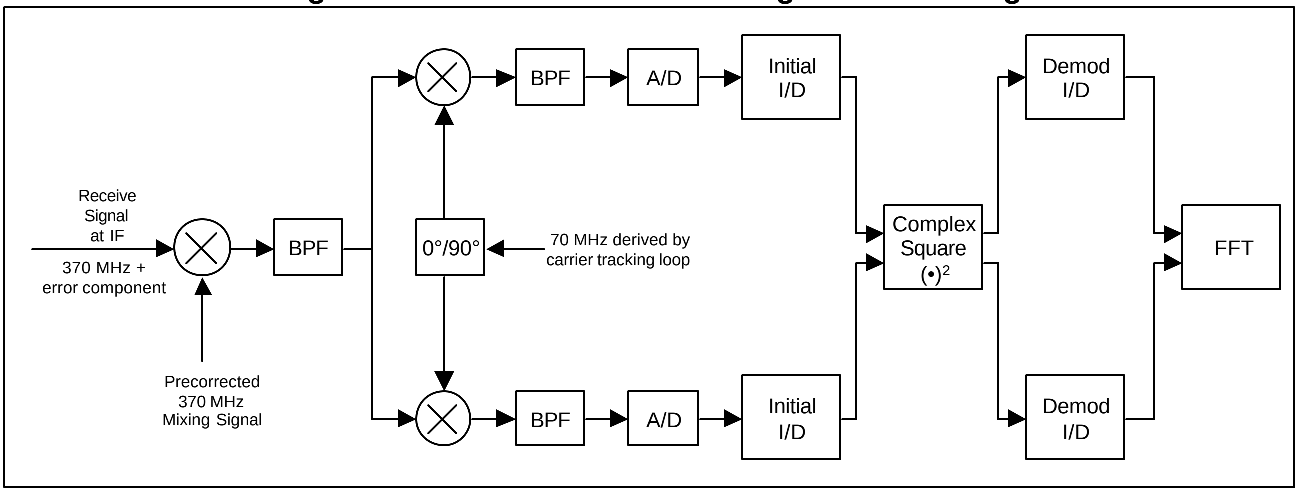


Figure C-2, Frame B shows the Initial I/D magnitude response squared and the PSD of the signal entering the Initial I/D including the spur. Figure C-2, Frame C shows the receive signal after the Initial I/D. It can be seen that a minimal amount of power is removed from both the desirable portion of the receive signal (at least in the frequency region of interest) and the spur. Figure C-2, Frame D shows the receive signal after the complex square. It should be noted that the plot is normalized such that the carrier power is 0 dB and the spur level is relative to this 0 dB carrier power. It can be seen at this point that the spur level is nearly 46 dB down from the carrier power.

Figure C-2, Frame E shows the Demod I/D magnitude response squared and the carrier and spur power levels. Figure C-2, Frame F shows the carrier and spur power levels after the Demod I/D. Again it should be noted that the carrier power is normalized to 0 dB and the spur level is relative to this 0 dB carrier power. It can be seen at the output of the Demod I/D that the spur level is over 42 dB down from the carrier power. Clearly the FFT peak search will identify the correct carrier frequency.

Figure C-1. Worst-Case Carrier Acquisition Scenario

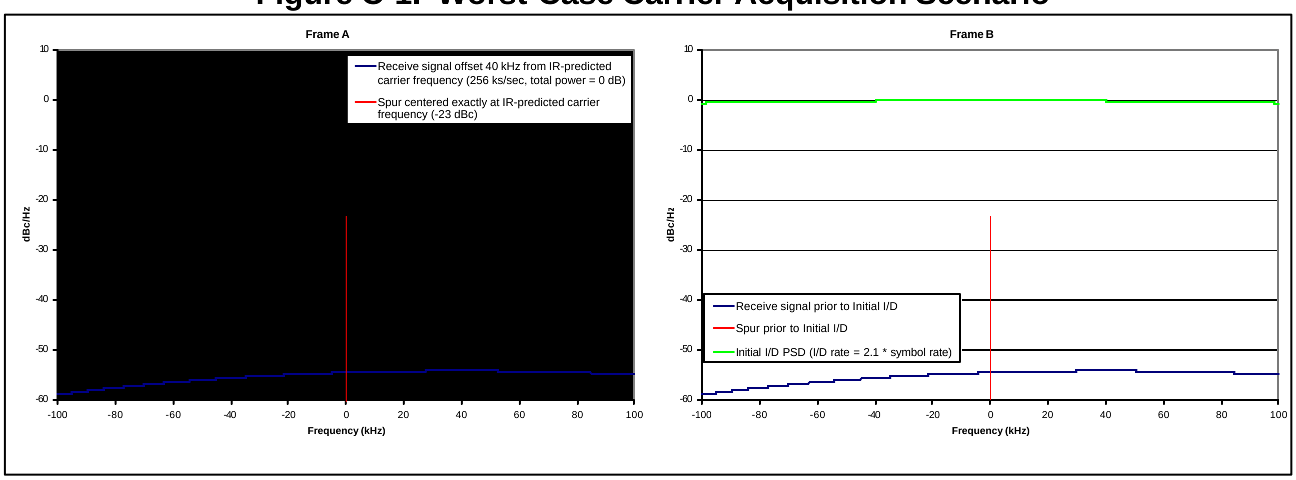
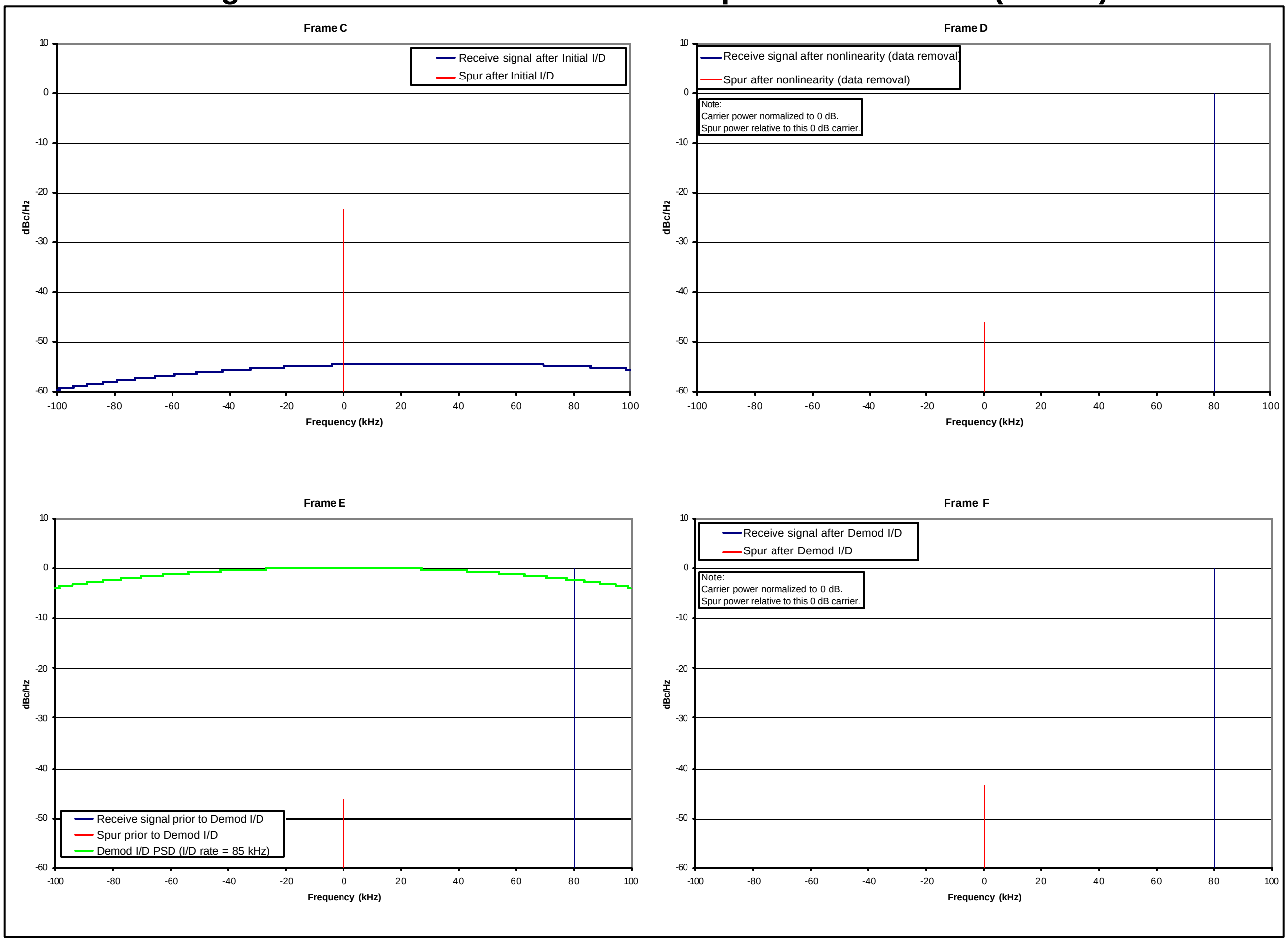


Figure C-1. Worst-Case Carrier Acquisition Scenario (cont'd)



The impact of relaxing the spurious outputs requirement on carrier tracking is expected to be negligible. The worst-case impact will occur when the spur is within one carrier tracking loop bandwidth of the actual carrier. Even under this circumstance, however, the higher-powered carrier will drive the loop operation, and the spur will make only a minimal contribution to loop operation.

APPENDIX D:
Analytical Validation of the ELV Frequency Stability Requirement

This appendix examines how the 530-SNUG frequency stability requirement can be relaxed for the ELV class of TDRSS users. This specification relaxation is possible due to the wider search range associated with the ELV user frequency uncertainty OPM capability (ELV user frequency uncertainty OPM expected to be used for ELVs) and the relatively short duration of ELV flights. The impact to carrier acquisition is expected to be an increase in acquisition time to no greater than 3 seconds. The impact to carrier tracking is expected to be negligible. Also considered an impact is the requirement that the ELV transmitter be characterized 24 hours prior to launch and the SHO be updated, and the ELV P_{rec} at TDRS must be $\geq$-202.0+12.0 dBW to ensure carrier acquisition at WSC.

D.1 Background

A brief summary of the IR carrier acquisition process is provided here. For additional details regarding the carrier acquisition process, the *SSA Equipment HWCI Specification* [10] should be consulted.

Carrier acquisition by the IR can be considered a two-step process. The first step is frequency pre-correction, the second step is actual carrier acquisition by the carrier tracking loop. Frequency pre-correction is the process whereby the IR predicts the input signal IF carrier frequency, searches ±40 kHz (ELV user frequency uncertainty OPM assumed) about this predicted frequency, locates the IF carrier frequency, and downconverts the IF signal with a frequency precorrected mixing signal to 70 MHz. The equation used by the IR to compute the frequency about which to perform the ±40 kHz sweep is as follows:

$$\hat{f}_{IR}(t) = 370.\overline{0}\ \mathrm{MHz} + \hat{f}_{off} + \hat{f}_{dev}(t)$$

where

$\hat{f}_{IR}(t) =$ Input IF carrier frequency predicted by the IR

$\hat{f}_{off} =$ Estimated user oscillator base frequency offset from the desired carrier frequency (a value assumed generally invariant over time in the range -250 kHz to 250 kHz and provided via the SHO)

$\hat{f}_{dev}(t) =$ Predicted frequency deviation due to user and TDRS motion (updated every 0.5 seconds)

Due to circumstances such as user ephemeris error and user oscillator frequency instability, the IF carrier frequency predicted by the IR, $\hat{f}_{IR}(t)$, will be off from the actual IF carrier frequency received by the IR. This expected error in the IR prediction necessitates the frequency sweep portion of the carrier acquisition process.

D.2 ELV Frequency Stability Specification Derivation

D.2.1 Introduction

For the ELV class of TDRSS users, it is expected that a frequency sweep range of ±40 kHz will be available. This indicates that the IR-predicted IF carrier frequency must be within ±40 kHz of the actual IF frequency entering the IR, otherwise, carrier acquisition will not occur. As noted in Section D.1, several factors drive the error in the IR-predicted IF carrier frequency estimate, of which, user oscillator frequency instability is one. This appendix examines the user oscillator frequency stability requirements necessary to ensure carrier acquisition for ELVs.

This analysis assumes the error in the IR-predicted IF carrier frequency is due strictly to the following two sources:

1. User oscillator frequency instability (time-varying frequency deviation about the center frequency provided in the SHO)
2. Inaccurate frequency profile provided to the IR due to user ephemeris error

This error in the IR prediction can be written as follows:

$$f_{IR}(t) - \hat{f}_{IR}(t) = f_{instab}(t) + f_{inacc\_freq\_prof}(t)$$

where

$f_{IR}(t) =$ Actual IF carrier frequency at the IR input

$\hat{f}_{IR}(t) =$ IR-predicted IF carrier frequency

$f_{instab}(t) =$ Frequency error (relative to center frequency provided via SHO) due to user oscillator frequency instability

$f_{inacc\_freq\_prof}(t) =$ Frequency error due to inaccurate frequency profile provided to IR due to the user ephemeris error

D.2.2 ELV Long-Term Frequency Stability Specification Derivation

Since the maximum frequency sweep range expected for the ELV class of TDRSS users is ±40 kHz, the difference between the IR-predicted IF carrier frequency and the actual IF carrier frequency must be less than 40 kHz for carrier acquisition to occur. This limit can be reflected in the frequency error equation as follows:

$$\left| f_{IR}(t) - \hat{f}_{IR}(t) \right| < 40000$$

or

$$\left| f_{instab}(t) + f_{inacc\_freq\_prof}(t) \right| < 40000$$

Per NASA direction, a conservative margin is to be included in the carrier acquisition frequency sweep budget. A ±13 kHz margin is selected, and the frequency error inequality which will be used to derive the ELV frequency stability requirements can be written as follows:

$$\left|f_{instab}(t) + f_{inacc\_freq\_prof}(t)\right| < 27000$$

The maximum error due to an inaccurate frequency profile as a result of a ±9 sec ephemeris error for noncoherent return S-band service is expected to be about 1 kHz [8]. It should be noted that an ephemeris error of less than ±0.1 sec is expected for ELVs, however, for the purposes of worst-case calculations, the specified worst-case amount of ±9 sec is used. The frequency error inequality can now be written as follows:

$$\left|f_{instab}(t)\right| < 26000$$

The ELV frequency stability requirement can now be derived based upon the above inequality. The format of the ELV frequency stability requirement will be a 48 hour observation time requirement, a 5 hour observation time requirement, and a 1 second averaging time requirement. This format is consistent with the *Space Network User's Guide* [1], the *Performance Specification for Services via the Tracking and Data Relay Satellite System* [4], and the *Performance and Design Requirements Specification for the Second Generation TDRSS User Transponder* [11].

The 48 hour frequency stability requirement can be derived as follows:

$$\left|(\text{48 hour frequency stability requirement})(\text{transmit frequency})\right| < 26000$$

$$\left|(\text{48 hour frequency stability requirement})(2300.0 \times 10^{6})\right| < 26000$$

$$\left|\text{48 hour frequency stability requirement}\right| < 11.3\ \text{ppm}$$

Note: This frequency stability requirement requires that the ELV transmitter be characterized 24 hours prior to launch. This ensures that the drift which occurs in a 48 hour period will be within the acquisition sweep range.

The ELV 5 hour frequency stability requirement will be derived by relaxing the existing 530-SNUG 5 hour frequency stability requirement by the same factor which the 530-SNUG 48 hour frequency stability requirement was relaxed. Since the existing 530-SNUG 48 hour frequency stability requirement is ±0.3 ppm, the factor by which the 48 hour requirement was relaxed by was 11.3/0.3, or 37.667. The existing 530-SNUG 5 hour frequency stability requirement is ±0.1 ppm, therefore, the ELV 5 hour frequency stability requirement will be ±0.1x(11.3/0.3) ppm, or ±3.77 ppm. The ELV long-term frequency stability requirement can be written as follows:

> The peak frequency deviation from the nominal carrier frequency normalized by the nominal carrier frequency shall be less than 11.3 ppm for a 48 hour observation time and less than 3.77 ppm for a 5 hour observation time

D.2.3 ELV Short-Term Frequency Stability Specification Derivation

The ELV 1 second frequency stability requirement cannot be derived in the same manner as the ELV 48 hour and 5 hour frequency stability requirements. The 1 second requirement is not constrained so much by the IR carrier acquisition frequency sweep range but, rather, by the IR carrier tracking loop stress limits. The wider frequency sweep range possible with ELV user frequency uncertainty OPM does not make it immediately possible to relax the existing 1 second frequency stability. An ELV 1 second frequency stability requirement is derived here, however, it is primarily as a result of taking full advantage of the IR carrier tracking loop capabilities.

For the expected ELV service configuration, the IR carrier tracking loop will be configured as a second-order loop with a damping factor of $1/\sqrt{2}$ and a bandwidth of 240 Hz during acquisition and 120 Hz during carrier tracking. Based upon these bandwidths, a reasonable specification for the 1 second frequency stability requirement would be a maximum frequency variation of half the carrier tracking loop tracking bandwidth, or ±0.026 ppm maximum. Per reference [12], carrier acquisition would be possible as the maximum frequency offset expected during acquisition would be less than the acquisition loop bandwidth. Additionally, carrier tracking would be maintained for a frequency step change of less than (2.61 x tracking bandwidth) [12]. The ELV short-term frequency stability requirement can be written as follows:

> The peak frequency deviation from the nominal carrier frequency normalized by the nominal carrier frequency shall be less than 0.026 ppm for a 1 second averaging time

D.3 Impact

Table D-1 provides a summary of the expected impact of relaxing the frequency stability requirement from the 530-SNUG specified values to the ELV values.

Table D-1. Expected Impact of Relaxing Frequency Stability Requirement

Performance Criteria	Expected Impact	
	Using 530-SNUG Spec	**Using Relaxed Spec**
BER Degradation	Negligible	Negligible
Carrier Acquisition	Acquisition time specified to be less than 1 sec for ±1.8 kHz sweep range. Acquisition time specified to be less than 3 sec for ±4.1 kHz sweep range.	ELV user frequency uncertainty OPM required Increase in acquisition time to 3 seconds (1)
Carrier Tracking	Negligible impact	Negligible impact. ELV frequency stability requirement derived considering cycle slipping likelihood and loss-of-lock likelihood

Notes:
1. Acquisition time specification currently does not exist for ELV user frequency uncertainty OPM search range, however, nominal acquisition time identified to be about 3 seconds.

APPENDIX E:
Analytical Validation of the ELV Phase Noise Requirement

This appendix examines how the 530-SNUG phase noise requirement can be relaxed for the ELV class of TDRSS users. The BER impact of this specification relaxation is about 0.1 dB for BPSK and 0.2 dB for QPSK. The impact to carrier acquisition and tracking is expected to be negligible.

E.1 Background

Unwanted phase modulation to the transmitter signal is comprised of two components, a discrete spectrum component and a continuous spectrum component. Phase noise is defined as the continuous spectrum portion of the unwanted phase modulation. Phase noise on the transmitter signal can be represented mathematically as follows:

$$\mathrm{s(t)} = \cos\left[w_{\mathrm{c}}\mathrm{t} + q + f_{\mathrm{d}}(\mathrm{t}) + f_{\mathrm{n}}(\mathrm{t})\right]$$

where

q = arbitrary phase of carrier

$f_{\mathrm{d}}(\mathrm{t})$ = data stream

$f_{\mathrm{n}}(\mathrm{t})$ = phase noise

When a signal containing phase noise is received at the ground terminal and mixed with the phase-locked carrier, the low-pass component of the output is as follows: (assuming PLL steady-state operation):

$$\mathrm{s(t)} \cdot 2\sin\left(w_{\mathrm{c}}\mathrm{t} + q - f_{\mathrm{n}}(\mathrm{t}) * \mathrm{h_{pll}(t)}\right)\Big|_{\mathrm{LP}} = \sin\left[f_d(\mathrm{t}) + f_{\mathrm{n}}(\mathrm{t}) * (d(\mathrm{t}) - \mathrm{h_{pll}(t)})\right]$$

where

$\mathrm{h_{pll}(t)}$ = receiver carrier tracking loop impulse response

As the function $h_{pll}(t)$ is a low-pass function, the function $(\delta(t) - h_{pll}(t))$ will be a high-pass function. If the bandwidth of $h_{pll}(t)$ is B Hz, then the bandwidth of $(\delta(t) - h_{pll}(t))$ will be B Hz. The quantity $f_{\mathrm{n}}(\mathrm{t}) * (d(\mathrm{t}) - \mathrm{h_{pll}(t)})$ generally is referred to as the untracked phase noise. This untracked phase noise is the portion of the input phase noise which goes on to impact the BER. The greater the untracked phase noise, the greater the impact to the BER.

E.2 Phase Noise Specification Derivation

Since the untracked phase noise is a high-pass version of the input phase noise, the PLL bandwidth can have a tremendous impact on the amount of phase noise passed by the PLL to the data detector. For the range of data rates expected for the ELV class of TDRSS users, the IR tracking loop bandwidth will be 120 Hz [5]. This means input phase noise less than 120 Hz offset from the carrier frequency will be filtered by the PLL. If no Doppler tracking is required for the ELV mission, a high phase noise requirement can be tolerated in the 1 Hz to 100 Hz region.

Using PNAT, a variety of candidate ELV phase noise requirements were considered. Knowing that the ELV phase noise below about 100 Hz offset from the carrier frequency was going to be filtered significantly, candidate ELV phase noise requirements with a very loose low frequency phase noise requirement could be considered. Table E-1 provides a summary of the phase noise requirement selected for the ELV class of TDRSS users.

Table E-1. Summary of ELV Phase Noise Specification(1)

Frequency Range Offset From Carrier	ELV Specification (deg., rms)
1 - 10 Hz	50.0
10 - 100 Hz	6.0
100 - 1k Hz	2.5
1k - 3M Hz (MA)(2)	2.5
1k - 6M Hz (SSA)	2.5

Notes:
1. For ELVs which cannot tolerate a Doppler tracking error greater than the specified 0.16 rad/sec, the 530-SNUG phase noise requirement must be used.
2. TDRS H,I,J era will include MA DG2 capability.

Figure E-1 provides a plot of a phase noise PSD which exactly meets the ELV phase noise requirement. Figure E-1 also provides a plot of the untracked phase noise PSD resulting from the ELV phase noise PSD being applied to a second-order PLL with a loop bandwidth of 120 Hz (IR carrier tracking loop characteristics). It can be seen that the ELV phase noise below about 100 Hz is dramatically filtered by the PLL. This demonstrates that a high phase noise requirement in the low frequency regions can be tolerated due to the high-pass filtering effects of the carrier tracking loop prior to the detector.

E.3 Impact

Table E-2 provides a summary of the expected impact of relaxing the phase noise requirement from the 530-SNUG specification to the ELV specification.

The BER degradation noted in Table E-2 was found using the BER degradation versus untracked phase error plots presented in Reference [8]. These plots are based upon the assumption that the phase noise at the input to the receiver is essentially Gaussian. This is a reasonable assumption as the phase noise at the input to the TDRSS receive equipment is the combination of many phase noise sources. Although the standalone transmitter phase noise is not Gaussian, it is expected that using the curves based upon input phase noise which is Gaussian is an accurate approximation.

Using the curves presented in Reference [8], it can be seen that an untracked phase error of 5.86° rms induces a BER degradation of about 0.13 dB to rate 1/2 coded BPSK and 0.25 dB to rate 1/2 coded QPSK.

Figure E-1. ELV Transmitter Phase Noise Before and After IR Demodulation

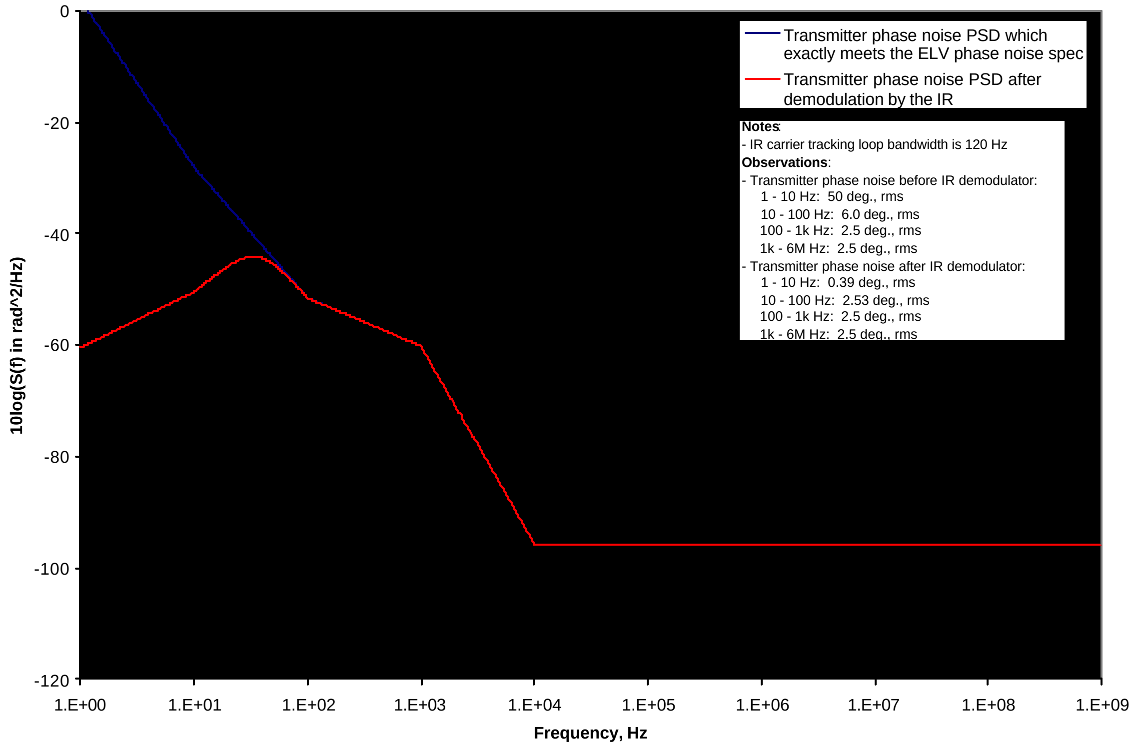


Table E-2. Impact of Relaxing Phase Noise Specification

Perfor-mance Criteria	Expected Impact[1, 2]			
	BPSK		QPSK	
	Using 530-SNUG Spec	Using Relaxed Spec	Using 530-SNUG Spec	Using Relaxed Spec
BER degradation	≈ 0.10 dB	≈ 0.15 dB	≈ 0.19 dB	≈ 0.25 dB
Carrier Acquisition	Negligible impact	Negligible impact	Negligible impact	Negligible impact
Carrier Tracking	Mean-time-to-cycle-slip specified to be > 90 minutes	Mean-time-to-cycle-slip expected to be >> 90 minutes. Loss of lock unlikely.	Mean-time-to-cycle-slip specified to be > 90 minutes	Mean-time-to-cycle-slip expected to be > 90 minutes. Loss of lock unlikely.
Doppler Tracking Error	< 0.16 rad/sec (1 sec averaging time)	< 3.79 rad/sec (1 sec averaging time) < 1.73 rad/sec (5 sec averaging time)	< 0.16 rad/sec (1 sec averaging time)	< 3.79 rad/sec (1 sec averaging time) < 1.73 rad/sec (5 sec averaging time)

Notes:
1. Assuming S-band ELV class user, i.e., rate 1/2 coded of data rate approximately 256 kb/sec with no Doppler tracking requirement.
2. Results based upon total untracked phase noise, i.e., ELV transmitter, TDRSS, and thermal noise contributions.

The carrier tracking impact noted in Table E-2 was determined by examining the impact of untracked phase error inside or just above the loop bandwidth on the mean-time-to-cycle-slip. Although conservative, this analysis considers all untracked phase error energy up to 1 kHz (recall the carrier tracking loop bandwidth is 120 Hz). Using PNAT, it can be shown that the total untracked phase error (includes all TDRSS contributors) in the 1 Hz to 1 kHz range is 4.53° rms when assuming a transmitter with phase noise performance equal to the relaxed phase noise specification. If this 4.53° rms untracked phase error amount is applied to traditional mean-time-to-cycle-slip equations based upon untracked phase noise due to thermal noise, an approximate mean-time-to-cycle-slip value can be computed.

Assuming a 120 Hz carrier tracking loop bandwidth and QPSK modulation, Figure E-2 provides a mean-time-to-cycle-slip versus inband (or just above) untracked phase error. This plot is based upon analysis presented in *Coherent Spread Spectrum Systems* [13]. From the figure, it can be seen that a 4.53° rms untracked phase error value will result in a mean-time-to-cycle-slip of nearly 10^5 seconds (or 27.8 hours). Assuming an user inband untracked phase error of 1° rms (530-SNUG specification for QPSK), a system mean-time-to-cycle slip much greater than 10^5 seconds can be expected. It should be noted that both estimates are well above the 90 minute mean-time-to-cycle-slip specification.

Figure E-2. Mean-Time-To-Cycle-Slip